

Luminosities and Space Densities of Short Gamma-Ray Bursts

Maarten Schmidt

California Institute of Technology, Pasadena, CA 91125

`mxs@deimos.caltech.edu`

ABSTRACT

Using the Euclidean value of $\langle V/V_{\max} \rangle$ as a cosmological distance indicator, we derive the isotropic-equivalent characteristic peak luminosity of gamma-ray bursts both longer and shorter than 2 s. The short bursts have essentially the same characteristic peak luminosity of 0.6×10^{51} erg $(0.064\text{s})^{-1}$ as do the long bursts. This may apply also to bursts with durations less than 0.25 s. The local space density of short bursts is around three times lower than that of long bursts.

Subject headings: cosmology: observations — gamma rays: bursts

1. Introduction

Since 1997, our understanding of gamma-ray bursts (GRB) has increased enormously through the optical identification of afterglows, determination of redshifts from optical spectra and generally from afterglow studies covering a large range of energies, from radio to X-rays. These studies suggest that GRBs are associated with massive stars and hence that the burst rate may be linked to the rate of star formation in galaxies. The number of GRBs so observed is still rather limited, and those successfully studied are all long bursts. We use the classification of GRBs in long bursts and short bursts based on the distribution of durations T_{90} in the BATSE data (Kouveliotou et al. 1993), which show a minimum around 2 s.

No afterglows have been observed so far for short bursts (Gandolfi et al. 2000). As a consequence, there is no direct knowledge of their redshifts, luminosities and space densities. There has been a suspicion that short GRBs would be at smaller redshifts and be of lower luminosities than long bursts, perhaps due to a remark in the abstract of a paper by Tavani (1998) that short bursts show little if any deviation from a Euclidean distribution but this is not supported by data discussed in the paper.

In this Letter, we briefly discuss efforts to derive the luminosity function of long bursts and then present a derivation of the characteristic peak luminosity L^* and the local space density for both long and short bursts. Even though the total gamma-ray energy may be physically of greater interest (Frail et al. 2001), we concentrate on peak luminosities since the detection of GRBs is based on count rates, not on the time-integrated flux or fluence of the burst.

Before any redshifts of GRBs were known, Mao, Narayan, & Piran (1994) used the Euclidean value of $\langle V/V_{\max} \rangle$ as a relative distance indicator to show that long and short bursts had the same peak luminosity to within a factor of 2, assuming they were standard candles. The redshifts that are now available for long bursts have led to the development of several luminosity indicators, such as the spectral lag derived from cross-correlation of two spectral channels (Norris, Marani & Bonnell 2000) and the variability in the time profile (Fenimore & Ramirez-Ruiz 2000). These luminosity indicators can in principle be used to derive the luminosity function of GRBs, including its evolution with redshift. Norris, Scargle & Bonnell (2001) have shown that the spectral lags for short bursts are much smaller than those of long bursts and conclude that the lag magnitude is discontinuous across the 2 s valley between long and short bursts.

We have used the Euclidean value of $\langle V/V_{\max} \rangle$ as a cosmological distance indicator to first derive characteristic luminosities (Schmidt 1999b) and then the luminosity function of GRBs (Schmidt 2001). This method, which makes use of a large sample of GRBs, circumvents the current weakness of methods based on the small number of redshifts observed so far. The price we pay for using $\langle V/V_{\max} \rangle$ as a distance indicator is that an assumption has to be made about the evolution of the luminosity function with redshift. We assume that this evolution tracks the star formation rate (SFR) on the expectation that GRBs are associated with massive stars. We employ the parametrizations of Porciani & Madau (2001), in particular their SFR model SF2 in which the co-moving space density rises by an order of magnitude near redshift $z = 1$ and then remains roughly constant for $z > 2$ (Steidel et al. 1999).

Our application of $\langle V/V_{\max} \rangle$ as a distance indicator used the BD2 sample (see Sec. 2) which is based on BATSE DISCLA data on a time resolution of 1024 ms. The resulting characteristic luminosities (Schmidt 1999b) and luminosity functions (Schmidt 2001) therefore applied to GRBs with a duration exceeding 1 or 2 s. In this Letter we employ the same method to derive characteristic luminosities L^* using the BATSE catalog. By using the GRBs detected with a time resolution of 64 ms, we can derive the L^* of short bursts. We will actually employ time resolutions of both 64 and 1024 ms, and obtain L^* for both short and long bursts, so that we can directly compare them.

In Sec. 2, we review the application of $\langle V/V_{\max} \rangle$ in deriving the luminosity function of long GRBs from the BD2 sample without using redshifts and recall the main results obtained. Following a discussion of data from the BATSE catalog in Sec. 3, we derive characteristic luminosities for both long and short GRBs in Sec. 4. The results are discussed in Sec. 5. Throughout this Letter, we use a flat cosmological model with $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

2. Luminosity Function Of Long Bursts Derived From The BD2 Sample

The BD2 sample of GRBs is based on BATSE DISCLA data consisting of the continuous data stream from the eight BATSE LAD detectors in four energy channels on a timescale of 1024 ms (Fishman et al. 1989). The sample was derived using a software trigger algorithm requiring an excess of at least 5σ over background in at least two detectors in the energy range 50–300 keV. The initial version was described in Schmidt (1999a) and a revision in Sec. 2 of Schmidt (1999b). The BD2 sample covers a period of 5.9 yr from TJD 8365 – 10528. It contains 1391 GRBs of which 1013 are listed in the BATSE catalog. The value of $\langle V/V_{\max} \rangle = 0.336 \pm 0.008$. The sample of 1391 GRBs effectively represents 2.003 yr of full sky coverage, corresponding to an annual rate of 694 GRBs.

The derivation of the luminosity function of GRBs (Schmidt 2001) was based on the correlation of the Euclidean value of $\langle V/V_{\max} \rangle$ with spectral hardness. Given that the Euclidean value of $\langle V/V_{\max} \rangle$ for a well defined sample of cosmological objects is a distance indicator, we interpreted the correlation of $\langle V/V_{\max} \rangle$ with spectral hardness as a luminosity-hardness correlation. The luminosity function was derived as the sum of the luminosity functions of four spectral hardness classes. It can be characterized approximately as consisting of two power laws of slopes -0.6 and -2 , respectively, with an isotropic-equivalent break peak luminosity of $\log L^* \sim 51.5$. The luminosity function ranges approximately from $\log L^* - 1.5$ to $\log L^* + 1.0$.

In the derivation of the characteristic luminosity L^* of GRBs from BATSE data in Sec. 4, we will assume that the shape and extent of the luminosity function is that of the broken power law just described and derive the value of $\log L^*$ from $\langle V/V_{\max} \rangle$. This is essentially the method used in Schmidt (1999a), where we varied the assumed extent and shape of the luminosity function to study the effect on the derived value of $\log L^*$.

3. Using Data From The BATSE Catalog

3.1. Evaluating V/V_{\max}

We will be using $\langle V/V_{\max} \rangle$ values derived from the BATSE 4B catalog¹ for bursts both longer and shorter than 2 s. Before we apply $\langle V/V_{\max} \rangle$ as a cosmological distance indicator, we consider how the individual V/V_{\max} values in the BATSE catalog are derived, and also how they are affected by the imposition of duration limits.

The BATSE catalog lists for individual bursts the count rate in the second brightest illuminated detector, C_{\max} , as well as the minimum detectable rate C_{\min} . The value of V/V_{\max} is then simply derived as $(C_{\max}/C_{\min})^{-3/2}$. In contrast, the values of V/V_{\max} in the BD2 sample have been derived through simulations, in which the burst is moved out in Euclidean space in small steps with a corresponding reduction in its amplitude. At each step, the full detection algorithm is re-employed to set the background and detect the burst. Once the burst is not detected any more, the value of V/V_{\max} is simply derived from the reduction factor. During this process of removal, the burst may get detected later and later depending on the time profile. The background time window, which precedes the detection by a fixed time interval, may start to include some burst signal. The final detection is usually made on the peak of the burst but in some cases where the burst signal preceding the peak is high and enters the background, the final detection may be off the peak. Given that in these cases upon removal the burst drops out earlier than expected from C_{\max}/C_{\min} , the actual value of V/V_{\max} will be larger. In practice, the effect depends much on the time profile. The net effect for a sample of bursts is that $(C_{\max}/C_{\min})^{-3/2}$ is an underestimate of $\langle V/V_{\max} \rangle$.

Next we consider the effect of imposing duration limits, such as $T_{90} < 2$ s. In the simulations carried out on the BD2 sample described above, we found that the duration of the burst decreased as it was moved out until at the limit of detection it was 1 or 2 s. A qualitatively similar effect has been described as a fluence duration bias for GRBs in the BATSE catalog (Hakkila et al. 2000). Suppose our sample is set by a restriction involving a limiting duration T_{lim} . In deriving V/V_{\max} , we should strictly apply two simultaneous limits, namely C_{\min} and T_{lim} , as was done in the first V/V_{\max} application (Schmidt 1968). However, evaluating the effect of T_{lim} on $\langle V/V_{\max} \rangle$ would require simulations of the derivation of T_{90} for BATSE GRBs which are not available. Therefore, we limit ourselves to finding the sign of the systematic error in $\langle V/V_{\max} \rangle$ if we ignore T_{lim} .

Consider the case of a GRB with a duration $T_{90} > T_1$. As we move the burst out, T_{90}

¹See <http://gamma-ray.msfc.nasa.gov/batse/grb/catalog/4b> catalog maintained by W. S. Paciesas et al.

will decrease and may become smaller than T_1 before it becomes undetectable. Therefore the reduction factor is smaller and V/V_{\max} is larger. Ignoring the lower limit T_1 leads to an underestimate of V/V_{\max} . In the case of an upper limit T_2 , a GRB with $T_{90} > T_2$ which does not belong to the sample, may become part of it when its T_{90} becomes shorter than T_2 upon removal. In this case, ignoring the upper limit T_2 produces a V/V_{\max} that is an overestimate. It should be emphasized that these considerations are purely qualitative; the actual effects depend on such factors as the time profile of the burst, the way the background is set, etc.

3.2. Effective Coverage

In order to derive the rate of GRBs per unit volume, we need to have an estimate of the effective full sky coverage of the GRB sample used. For the BD2 we have evaluated the efficiency at 33.8% leading to an effective full sky coverage of 2.003 yr (Schmidt 1999a). The total sample of 1391 GRBs then corresponds to a rate of 694 GRB yr^{-1} .

The 4B catalog gives an annual rate of 666 GRB yr^{-1} , presumably based on the most sensitive detections, which are at the 1024 ms timescale. Considering that the S/N limit of the 4B catalog is 5.5σ and that of the BD2 sample 5σ , these rates are quite consistent. We only consider GRBs detected while the BATSE on-board trigger was set for 5.5σ over the energy range 50 – 300 keV. Among those, the 4B catalog contains 612 GRBs for which $C_{\max}/C_{\min} \geq 1$ at the 1024 ms timescale (those < 1 were detected at time scales of 64 ms or 256 ms). This corresponds to an effective full sky coverage for the purpose of this work of 0.92 yr. We assume that this value also applies to the 64 ms timescale.

4. Characteristic Luminosities For Long and Short Bursts

The method used to derive the isotropic-equivalent characteristic peak luminosity L^* for a given value of $\langle V/V_{\max} \rangle$ is essentially the same as that used before (Schmidt 1999b). Based on our discussion of long bursts in Sec. 2, the local luminosity function of peak GRB luminosities L , defined as the co-moving space density of GRBs in the interval $\log L$ to $\log L + d \log L$, is

$$\Phi_o(L) = 0, \quad \text{for} \quad \log L < \log L^* - 1.5, \quad (1a)$$

$$\Phi_o(L) = c_o (L/L^*)^{-0.6}, \quad \text{for} \quad \log L^* - 1.5 < \log L < \log L^*, \quad (1b)$$

$$\Phi_o(L) = c_o (L/L^*)^{-2.0}, \quad \text{for} \quad \log L^* < \log L < \log L^* + 1.0, \quad (1c)$$

$$\Phi_o(L) = 0, \quad \text{for} \quad \log L > \log L^* + 1.0. \quad (1d)$$

We assume that the GRB rate as a function of redshift follows the SFR model SF2 (see Sec. 1). The median value of the spectral photon index for the (long) bursts in the BD2 sample is -1.6 (Schmidt 2001). For the short bursts we adopt an index of -1.1 to reflect their larger average hardness ratio (Kouveliotou et al. 1993).

The median 4B limiting photon flux for 1024 ms detection in the $50 - 300$ keV range, including the effect of atmospheric scattering, is $0.25 \text{ ph cm}^{-2} \text{ s}^{-1}$ (Meegan et al. 1998). We adopt the same value for the BD2 sample for which atmospheric scattering has not yet been evaluated. For GRBs detected on the 64 ms timescale, the derivation of L^* from $\langle V/V_{\max} \rangle$ is carried out on this timescale, so the resulting luminosity L^* is produced in ergs $(0.064\text{s})^{-1}$. In order to convert to this system from a timescale of 1024 ms, we compared for GRBs with $T_{90} > 2$ s their peak fluxes at timescales 1024 ms and 64 ms given in the BATSE catalog. The average 1024/64 flux ratio is 0.68, reflecting the variability of long GRBs at their peak at subsecond timescales. Accordingly, we convert peak luminosities per 1024 ms into ones per 64 ms by dividing by $0.68 \times 16 = 10.9$.

In order to provide a comparison with past work, we first derive L^* for long bursts. The top line of Table 1 shows the results for the BD2 sample of GRBs. The value of L^* is 70% larger than that found from the more sophisticated derivation in Schmidt (2001), which involved splitting the sample in groups of different spectral hardness. The resulting luminosity function was not exactly a broken power law, which causes the above difference.

The remaining entries in Table 1 are all based on data from the 4B catalog. The first three can be directly compared with the BD2 results since they all concern long bursts. The $\log L^*$ values show a range of 0.3, with a systematic offset of around $+0.2$ from the BD2 value. The local densities are systematically lower than that from the BD2, partly due to the higher luminosity.

The next row of Table 1 gives the results for short bursts with $T_{90} < 2$ s. The characteristic peak luminosity L^* is in the middle of the range given for long BATSE bursts. The local space density of short bursts is ~ 3 times smaller than that of long bursts. In order to investigate whether there might be a trend among the short bursts, we show further results for $T_{90} < 0.5$ s and < 0.25 s. The formal mean errors in $\log L^*$ for the short bursts are ± 0.20 , ± 0.25 , and ± 0.35 , respectively. We see no trend of $\log L^*$ with duration among the short bursts.

5. Discussion

The systematic effect of using C_{max}/C_{min} in the derivation of $\langle V/V_{max} \rangle$ discussed in Sec. 3 applies to all BATSE entries in Table 1. Therefore all values of $\langle V/V_{max} \rangle$ are systematically too small, and the resulting values of $\log L^*$ too large. The actual effect is hard to estimate because it depends on the burst profiles and the methodology of setting the background. For the BD2 sample we find that using C_{max}/C_{min} results in an underestimate of $\langle V/V_{max} \rangle$ of 0.009 leading to an overestimate of $\log L^*$ by 0.08. Considering this offset the agreement between the first two rows of Table 1 is satisfactory considering that the formal errors (derived from the mean errors of $\langle V/V_{max} \rangle$) in $\log L^*$ are ± 0.07 and ± 0.10 , respectively. For the BATSE bursts with $T_{90} > 2$ s in the next two rows of Table 1, the systematic effect caused by the duration limit may result in an overestimate of $\log L^*$, but no obvious effect is evident.

The short bursts with $T_{90} < 2$ s have a value of $\log L^*$ that is entirely consistent with that of the long bursts. The systematic effect of the upper limit for the duration will be an underestimate of $\log L^*$. This effect may well be small for short bursts, but only simulations can tell.

The peak luminosities and local space densities given in Table 1 are isotropic-equivalent values and are all based on SFR model SF2 (Sec. 1). If, instead, we use SFR models SF1 or SF3 the derived values of $\log L^*$ typically change by -0.17 and 0.14 , respectively, essentially the same for short and long bursts.

Assuming that the BATSE values of $\log L^*$ are offset by $+0.08$, we find that for our given assumptions about the shape and the evolution of the luminosity function, long bursts with $T_{90} > 2$ s and short bursts with $T_{90} < 2$ s have the same value of the characteristic peak luminosity $L^* \sim 0.6 \times 10^{51}$ erg $(0.064\text{s})^{-1}$. As a consequence, short bursts will have lower radiated energies than long bursts, which may have a major effect on the afterglows of short GRBs (Panaitescu, Kumar, & Narayan 2001). Among the short bursts there is no evidence for any substantial change in L^* for durations as short as 0.25 s.

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Table 1. Characteristic Luminosity and Space Density From Various GRB Samples.^a

Sample	Δt	T_{90}	n	$\langle V/V_{\max} \rangle$	α	f_{lim} ^b	$\log L^*$ ^c	ρ_o ^d
BD2	1024 ms		1391	0.336 ± 0.008	-1.6	0.25	50.67	0.339
BATSE	1024 ms		612	0.312 ± 0.012	-1.6	0.25	50.88	0.240
BATSE	1024 ms	> 2s	469	0.291 ± 0.013	-1.6	0.25	51.05	0.147
BATSE	64 ms	> 2s	323	0.376 ± 0.016	-1.6	1.00	50.72	0.250
BATSE	64 ms	< 2s	141	0.354 ± 0.023	-1.1	1.00	50.92	0.075
BATSE	64 ms	< 0.5s	91	0.361 ± 0.029	-1.1	1.00	50.86	0.040
BATSE	64 ms	< 0.25s	49	0.347 ± 0.042	-1.1	1.00	50.98	0.023

^aWe use $H_0 = 65$ km s⁻¹ Mpc⁻¹, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

^b f_{lim} is the limiting flux in ph cm⁻² s⁻¹ over the energy range 50 – 300 keV.

^c L^* is the isotropic-equivalent characteristic peak luminosity in erg (0.064s)⁻¹ in the 50 – 300 keV band.

^d ρ_o is the local ($z = 0$) GRB rate, in units of Gpc⁻³ yr⁻¹.